

LIDAR and Numerical Modeling Studies of Small-Scale Lateral Dispersion in the Ocean

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LONG-TERM GOALS

Our long-term goal is to better understand lateral mixing processes on scales of 0.1-10 km in the ocean. This includes the underlying mechanisms and forcing, as well as the temporal, spatial, and scale variability of such mixing. The particular goal of the present work is to directly observe the processes governing lateral stirring at these scales via high resolution dye release experiments using airborne LIDAR. The broad impacts of this research range from a better understanding of ocean ecosystems and ocean health, to improved parameterizations in numerical models, to a variety of other practical purposes.

OBJECTIVES

This annual report marks the end of year 2 of a 5 year study as part of the “Scalable Lateral Mixing and Coherent Turbulence” (a.k.a., LatMix) DRI. The goal of the present work is to conduct a series of dye release experiments in the seasonal pycnocline and upper ocean to understand lateral dispersion and frontal processes on scales of 10 m to 10 km. The main effort of the present work is a collaboration between J. Ledwell and E. Terray (WHOI), M. Sundermeyer (UMass Dartmouth), and J. Prentice and B. Concannon (NAVAIR).

This project is being performed jointly with a collaborative NSF grant to J. Ledwell, E. Terray, and M. Sundermeyer (see “Related Projects” below). ONR is providing support for the airborne LIDAR operations, and is supplementing our efforts in the field and in analysis under the NSF support.

APPROACH

The vertical and horizontal dispersion and advection of dye release experiments will be monitored on spatial scales of meters to several kilometers in the horizontal, 1-10 meters in the vertical, and on time scales of minutes to hours, up to 4 days. Sampling of the dye will be performed using airborne LIDAR, as well as *in situ* sensors lowered and towed from a ship. Additional measurements of optical characteristics, hydrography, currents, and internal wave characteristics will be used to identify particular driving mechanisms of the observed dispersion. The dye experiments will be coordinated

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with AUV and microstructure measurements by other investigators to discern forcing mechanisms responsible for the dispersion. The dye experiments will also be guided by numerical modeling process studies by other investigators under the DRI, and will provide data for testing such models.

In the context of the DRI modeling efforts, M. Sundermeyer is also collaborating closely with M.-P. Lelong in support of her DRI grant, “LES Modeling of Lateral Dispersion in the Ocean on Scales of 10 m – 10 km.” As part of this, numerical simulations and analysis are being performed under the present effort in preparation for, and to aid interpretation of, the main field studies. These numerical simulations are also being coordinated with modeling efforts of other DRI participants.

WORK COMPLETED

An engineering field experiment (cruise plus overflights) to test the primary capability of the airborne LIDAR was conducted between the Ledwell/Terray/Sundermeyer group and the NAVAIR LIDAR group in September, 2008, and was reported on in our FY08 annual report under grant number N00014-08-1-0545. A second engineering field test / pilot cruise to test a variety of new in situ sensors / capabilities of both the Ledwell/Terray/Sundermeyer group, as well as two other LatMix field groups was conducted in August, 2010. The main field efforts for LatMix will be conducted in June, 2011 and spring 2012.

Our main efforts in the current reporting year have been to acquire and test a variety of new sensors, to help plan and participate in a virtual experiment, and to plan for the 2010 test cruise and 2011 and 2012 field efforts. To this end, we have completed the following work:

- 1.) We participated in two planning meetings for the LatMix DRI, the first in Seattle, WA in Dec, 2009 (focused on the observational effort), the second in Boston, MA in July, 2010 (focused on the numerical modeling effort). We also continue to exchange information with other DRI participants toward planning and coordinating LatMix field efforts, numerical modeling studies, and theoretical analysis.
- 2.) We participated in a virtual experiment in June, 2010, in which both field and numerical modeling DRI participants exchanged ideas and did a 5-day “dry run” of how we might choose a field site in the main 2011 field experiments. Goals of the virtual experiment included assessing what information from remote sensing and modeling data would be useful in selecting particular features to sample, determining what additional data and modeling products would be useful in this process, establishing consensus among the PIs on how we would select a field site based in available information, and testing/debugging the flow of data through the LatMix real-time data servers that will be used during the field experiments.
- 3.) Under separate funding (DURIP and collaborative NSF – see “Related Projects” below), we acquired new field instrumentation that will be used in the upcoming LatMix DRI / NSF field experiments. This includes a SATLANTIC Apparent Optical Properties System, a WetLabs ACs spectral absorption/attenuation sensor, a Sea Sciences Acrobat tow sled, and a new micro CTD and fluorometer sampling package for small-scale surveys of the dye patches. Over the past year, we have performed the necessary bench/field testing of these instrument systems, and we successfully used all of them during the August 2010 engineering test cruise. In particular we gained experience on the August cruise in using the WetLabs integrated sensor package to measure intrinsic optical properties in very clear waters. These measurements, together with the SATLANTIC

measurements of the diffuse attenuation coefficient will be used in the inverse modeling to constrain the solution.

- 4.) We conducted and have begun analyzing data from an engineering field test / pilot cruise performed in August, 2010 in the Sargasso Sea, southeast of Cape Hatteras (Fig 1). Cruise participants included the WHOI and UMass dye PIs, the OSU dye group (Levine), and the OSU glider group (Shearman) (cruise report forthcoming). Also part of this field effort was the testing of the LatMix realtime data site, coordinated by R. Harcourt at APL/U. Washington. Major components of the realtime data aspect of the test included verifying the ability to transfer data from the UW server to the ship in real time, as well as tracking of satellite tracked drifters and other assets in the water

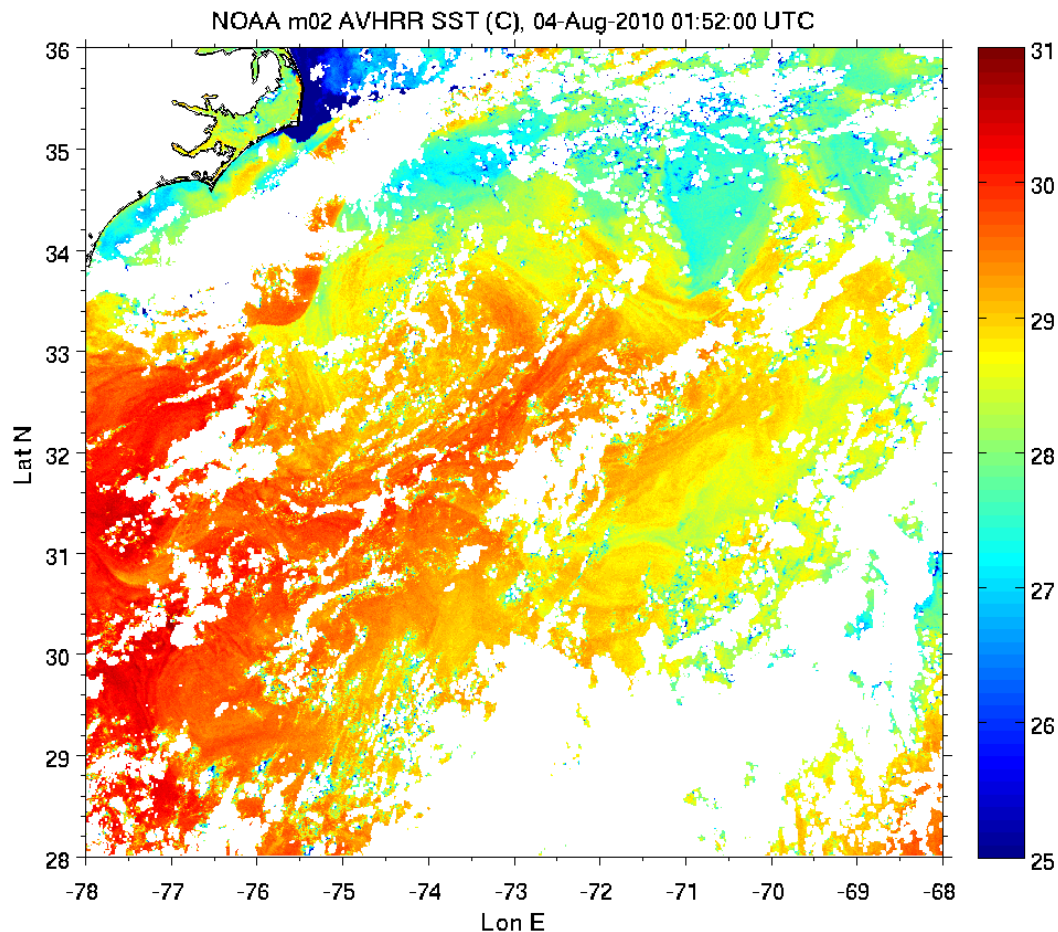


Figure 1. Sea Surface Temperature map of study region SW of Cape Hatteras, NC. Arrow and box show approximate location of August 2010 pilot field experiment.

- 5.) We continue to work with the NAVAIR LIDAR group, led by Drs. Jennifer Prentice and Brian Concannon, to identify system parameters for their new LIDAR system that optimally enable them to detect and map fluorescent dye patches, to understand the impact of the new system modifications, and to prepare for the real-time and post-processing data analysis tasks that will be required during and after the 2011 field experiments. The primary modifications of the LIDAR

system to allow surveying of our dye patches were performed over the past reporting year. Additional system tests are ongoing, and are on schedule to be completed in winter, 2010, in advance of the June 2011 field effort.

- 6.) We continue to explore and develop improved methods for inverting LIDAR waveforms to obtain absolute dye concentrations following our work under previous funding (Terray et al., 2005; Sundermeyer et al., 2007). This includes consideration of LIDAR system characteristics, and ocean optical properties, including effects of multiple scattering. In collaboration with the NAVAIR group we have put together analysis routines to register the LIDAR measurements of fluorescence intensity onto a uniform 3-dimensional grid. Work to invert these observations to estimate dye concentration is ongoing.
- 7.) As part of the modeling efforts in collaboration with M.-P. Lelong, we continue to conduct numerical simulations pursuant to one of the hypotheses of the LatMix DRI, involving localized internal wave breaking and subsequent lateral stirring by the relaxation of diapycnal mixing events. In the current reporting year we have continued to examine the details of such wave breaking events and mixed patch adjustment, with the goal of better understanding the processes leading to sub-mesoscale lateral dispersion. We have also been examining the effects of large-scale shears and strains, and of intermittency, on the vortical mode stirring mechanism. These simulations will also guide field efforts in distinguishing among different possible lateral mixing processes.

RESULTS

An engineering field test was conducted in August, 2010 on R/V Cape Hatteras, in collaboration with the OSU dye and glider groups (Levine and Shearman, respectively), with Ledwell as chief scientist. Two dye release experiments were performed southeast of the Gulf Stream off North Carolina near density fronts (Fig. 1). The sites for these releases were chosen on the basis of satellite images of sea surface height and temperature and model results for near surface velocity and the potential for fronts to strengthen. These images were made available on the web by R. Harcourt at APL/UW and J. Molemaker at UCLA. Part of our aim was to test the practicality of such data transfers and also of the usefulness of the images in helping to choose sites. This part of the program succeeded in both respects.

Both dye releases were on an isopycnal surface whose mean depth was approximately 25 m. The dye, three or four drogued drifters, and the OSU glider were deployed successfully, and the dye was sampled with the OSU Moving Vessel Profiler and the UMass towed Acrobat. The dye patch drifted at a speed of about 25 cm/s in both cases. Nevertheless the drifters and integration of the 25-m bin of the ship's ADCP enabled us to stay with the dye patches.

In the first experiment, which lasted 21 hours, whatever front was there was weak. The dye was sampled thoroughly (Fig. 2). In the second experiment, lasting 67 hours, the front was stronger and only weak dye signals were found after the first day. It is possible that a large portion of the dye crossed into the mixed layer where it was diluted by vertical mixing and displaced from the center of our activities by shear. An airborne survey of the dye would have been very helpful in this case. (Airborne surveys with LIDAR were intended to be tested during this cruise, but the aircraft had not been certified to fly with the LIDAR by the time of the cruise.) In any case, further analysis of the data will be required to try to find out the fate of the dye.

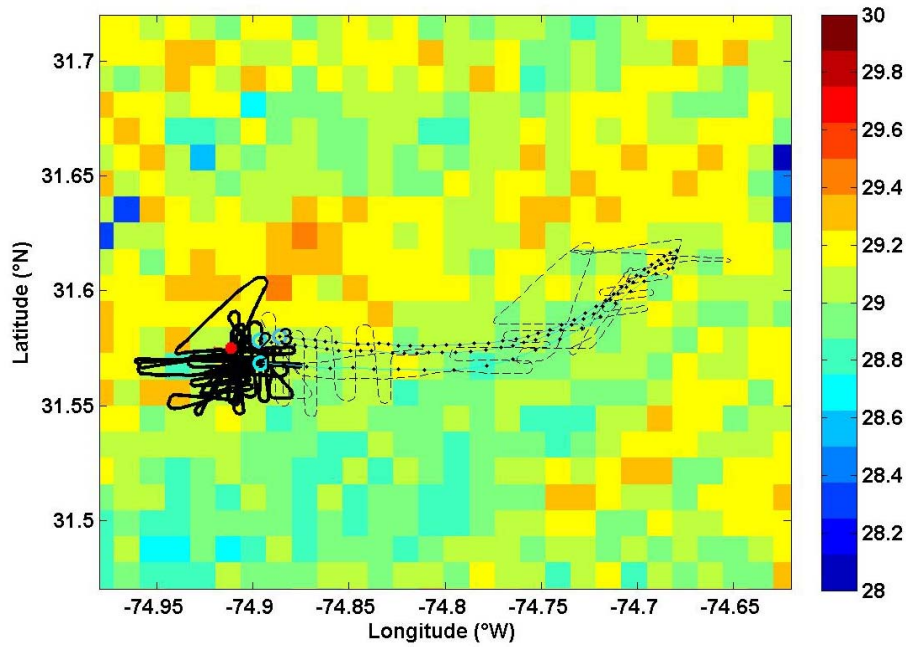


Figure 2. Ship track in Earth (light dashed line) and advected Lagrangian (bold black line), drifter tracks (thin line with dots at GPS fix locations), and SST (background color) for first 24 hr experiment performed during August 2010 LatMix test cruise. A clear SW advection of the dye patch and drifters is apparent (ship track followed dye). Note also the dominant features in the SST image, aligning roughly with the direction of the flow.

This field test succeeded in testing the following components of the project components, most of which were new to us: Drogue system (new design; Sundermeyer), Dye release system (new control program; Ledwell and Terray), Moving Vessel Profiler (new instrument; Levine), Acrobat (new instrument; Sundermeyer), Satlantic apparent optical properties system (new; Ledwell and Terray), WetLabs inherent optical properties system (new; Ledwell and Terray), and the OSU glider (Shearman). As mentioned above, we also tested communications from drogues to shore to ship and the packaging and sending of satellite images and model output from shore to ship (R. Harcourt).

Regarding our modeling work, simulations have been performed to examine the propagation, deformation, and breaking of a nonlinear wave packet through an ambient linear stratification. Momentum, total potential energy, and available potential energy have been analyzed in an attempt to quantify the breaking, and to understand the detailed nature of the diapycnal mixing events whose adjustment are believed to lead to lateral dispersion. The major results of this work were reported in our 2009 annual report. A manuscript on this work was recently submitted to *Physics of Fluids* (Birch and Sundermeyer, submitted).

We have also continued our work to examine the effects of large-scale shears and strains on vortical mode generation and resultant stirring. Our primary result in this area is that the stability of a vortex generated through mixed patch adjustment depends on the strength of the background shear field. In particular, simulations of a single vortex in the presence of a large scale internal wave can go unstable to two types of instability, baroclinic, driven by the vertical shear associated with the wave, or barotropic, driven by the horizontal shear associated with the vortex itself. A manuscript on this work

is in its final stages of preparation for submission (Brunner-Suzuki et al., in prep). Ongoing simulations will examine the impact of such stability/instability on the effective lateral stirring generated by a random superposition of such vortices.

WORK UNDERWAY

A report on the August cruise is underway, as is post-cruise analysis of the data, in collaboration with the other PI's on the cruise who were responsible for the instruments which gathered the dye data. Planning of needed tests of the LIDAR system prior to the main experiments, which start in June 2011, is underway. Ledwell, who has assumed the role of chair of the steering committee for the LatMix DRI, is coordinating the 3-ship operation in June 2011. Cruise dates and ships have been scheduled. Ledwell has also been leading the planning of a meeting of the DRI PIs in winter of 2011. Terray continues to act as liaison with Brian Concannon at NAVAIR, and to develop techniques to invert LIDAR signals for dye distribution.

RELATED PROJECTS

The above work and findings represent a joint effort on the part of LatMix DRI PIs Ledwell and Terray (WHOI) and Sundermeyer (UMass Dartmouth) under ONR grants N00014-09-1-0175 and N00014-09-1-0194, respectively. The work is done in concert with the DRI Scalable Lateral Mixing and Coherent Turbulence.

Field instrumentation to be used in the DRI field work was purchased in part under DURIP grant N00014-09-1-0825, and in part under a related NSF project entitled "Collaborative Research: LIDAR Studies of Lateral Dispersion in the Seasonal Pycnocline", NSF Awards OCE-0751734 (UMass) and OCE-0751653 (WHOI).

The PIs efforts under the ONR LatMix DRI are being performed in coordination with the PIs efforts under the above mentioned NSF Awards OCE-0751734 (UMass) and OCE-0751653 (WHOI).

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PUBLICATIONS

Birch, D. A., M. A. Sundermeyer, Breaking internal wave groups: Mixing and momentum fluxes, Submitted to: *Phys. Fluids*.

Brunner-Suzuki, A.-M., M. A. Sundermeyer and M.-P. Lelong, Vortex Stability in a Large-Scale Internal Wave Shear. In Prep.